Space Vehicle Systems Analysis: MSFC Tools and Processes

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ABSTRACT

The Advanced Concepts Office at the Marshall Space Flight Center is an organization that can trace its roots to the days just before the launch of the Saturn launch vehicles and has distinguished itself for systems engineering and systems analysis necessary to define the future of the center and Agency. Systems analysis has evolved considerably in recent history and as computing power and knowledge has increased, the processes by which concept trade decisions are made have evolved comparably. This paper will describe the processes and tools used at Marshall Space Flight Center in the Advance Concepts Office and the Engineering Directorate Vehicle Integrated Performance Analysis (VIPA) team, the products generated using these tools and processes and future plans for further development of capabilities for advance transportation systems for the exploration of near Earth space and deep space; both human and robotic.

1.0 Introduction

The Advanced Concepts Office of the Marshall Space Flight Center has been quite instrumental in establishing the rich technical heritage that has become the legacy of NASA. Program Development was established in the early 70’s to begin planning for future programs that would follow Apollo and lead to further exploration of space. The systems analysis process, tools and techniques were based in a multi-disciplinary study team performing conceptual design and detailed design studies. The preliminary design office was a much smaller version of the massive engineering directorate of the Marshall Space Flight Center; containing all of the engineering disciplines needed to perform a complete spacecraft design. However, the preliminary design office’s function was to assess the feasibility of new ideas or develop new ideas. Whereas, the Engineering Directorate’s function was to perform the detailed analyses necessary to complete the design and support hardware development and operation.

In recent history, the Program Development Office was dissolved and the early conceptual design function was retained in the form of the Advanced Concepts Office. The goal of the this even smaller team of engineers was to perform low fidelity systems analyses to explore broad concept trade spaces, develop concepts for further study, and perform feasibility studies. The detailed trade study function was developed within the Engineering Directorate’s Vehicle Integrated Performance Analysis (VIPA) process.

1.1. Advanced Concepts Development

The Advanced Concepts Office is a team of systems engineers and multi-disciplinary design engineers that perform architectural analyses and conceptual designs for various space vehicle concepts. These concepts range from launch vehicle concepts to in-space transportation stages. Architectural analyses are one of the first steps in the systems engineering process enabling an adequate assessment of the vehicle concepts. Without a proper understanding of the architectural requirements, the vehicle definition is baseless and possibly errant.

The office has the skills, knowledge, and tools necessary to develop expendable and reusable concepts for launch vehicles. The Space Launch Initiative (SLI), Next Generation Launch Technologies (NGLT) and the Crew Launch Vehicle (CLV) concepts were developed and studied in the Advanced Concepts Office. In addition to Earth-to-Orbit (ETO) vehicles, in-space vehicles using chemical propulsion and advanced propulsion concepts may be analyzed and studied. Development of these concepts requires more subsystem inputs than that of the launch vehicles. The tools to model the missions and calculate the performance of the concepts are different as well requiring the ability to model the performance of various concepts using low or high thrust performance tools.

Figure 1 provides an overview of the Advanced Concepts Office at MSFC. Indicated in the figure are some of the concepts that have been studied at MSFC. Examples shown are of the advanced in-space vehicle concepts developed for the Revolutionary Aerospace Systems Concepts (RASC) studies, launch vehicle systems, crewed vehicle systems and chemical upperstages. Also, shown is the MSFC Collaborative Engineering Center (CEC) which has been used extensively in the development of these concepts in both in-house and multi-center collaborations. Additionally, some of the tools, processes and output from those tools are shown. These tools and processes will be discussed in more detail later.

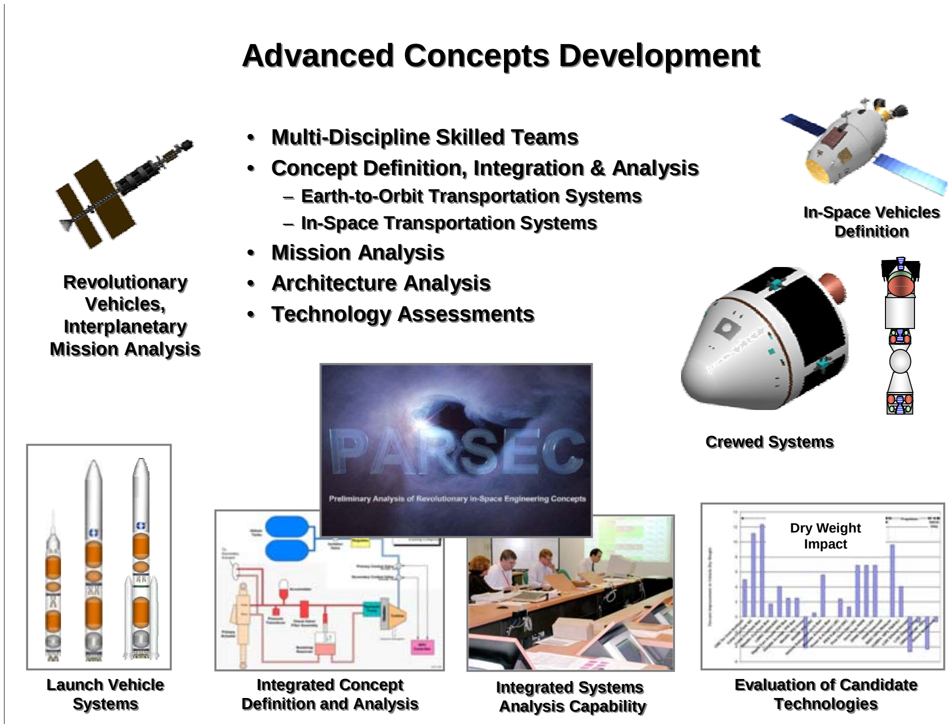

Figure 1. Advanced Concepts Office Overview

1.1.1 Concept Development and Technology Evaluation

Figure 2 shows the general process used for technology evaluation in Advanced Concepts. The process begins with understanding the program requirements. Typically, these would manifest themselves in the form of Level 0/1 requirements, design reference missions and/or program figures of merit (FOMs). Oftentimes these are not provided and it becomes a function of the lead systems engineer to provide or aid in the development of these. Without this information, it becomes very difficult to perform a trade study that will yield useful and consistent results.

Next, through the combined efforts of the customer, the lead systems engineer and a subset of the systems analysts, the trade space is developed with numerous concepts and ideas with appropriate technologies that may meet the specified requirements. This trade space often is shown in the form of a trade tree. The usefulness of the trade tree is that it provides a graphical representation of the trade space and enables a disciplined approach to reducing the trade space to a manageable set of concepts for further analyses. Often, the first examination of the trade space involves the systems engineer and the discipline engineers using technical experience and sound engineering judgment to remove or “chop off” branches of the trade tree that have minimal technical merit or which can be easily shown to be technically infeasible.

With a manageable set of concepts, the multi-disciplined technical team develops models of the concepts used to define the systems and subsystems of the spacecraft. At the lowest fidelity level these models are spreadsheets with simple estimations of engine performance and subsystem weights. However, more detailed weights modeling and performance assessments may be achieved using more detailed tools. For launch vehicles, these models include an ETO ascent performance tool, a structural loads and analysis tool, and a weights and sizing tool. Additionally, cost, reliability, and operations models are incorporated in the analyses. With all of the models in place, the concept definition may be completed taking into account vehicle technical performance along with cost, operations, and reliability. FOM’s are evaluated based on the results of these analyses. As necessary, technology is evaluated to help programs understand how to fund development.

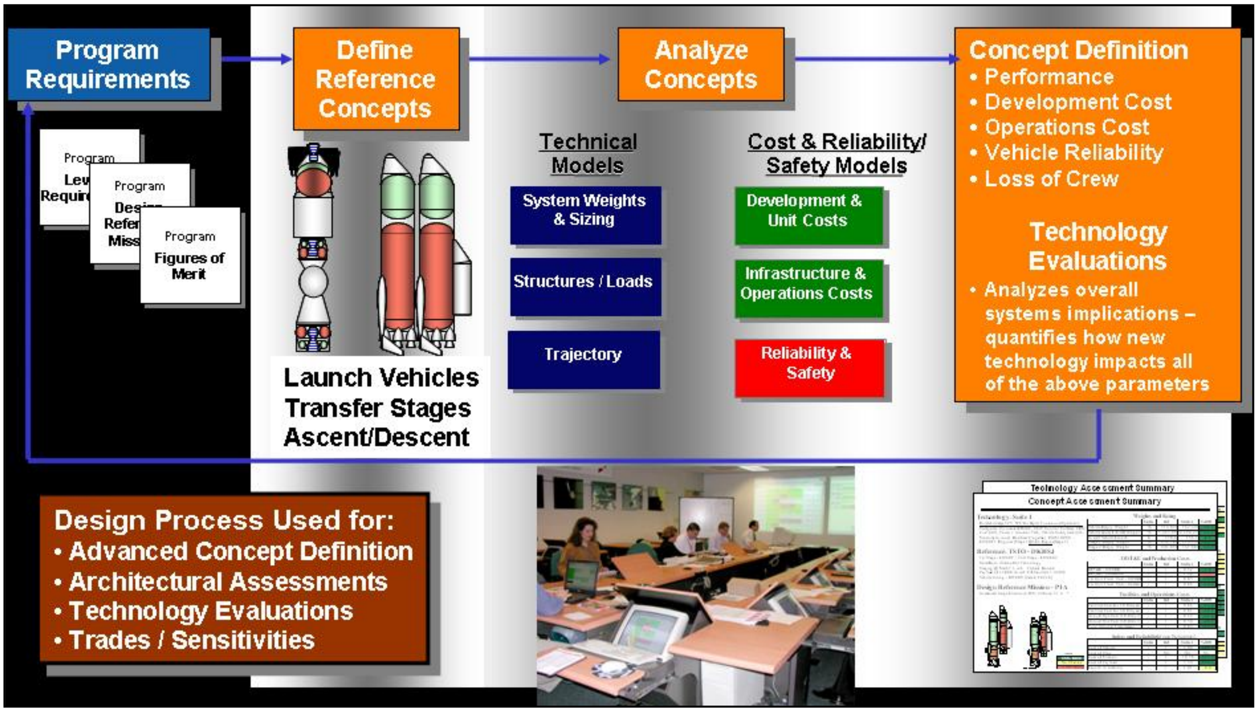

Figure 2. Concept Definition and Technology Evaluation

1.2. Analysis Tools

Figure 3 is an example of an analysis specific to an ETO concept. Shown are the tools used for this specific analysis. In this example, once the ground rules and assumptions have been defined, the technical analysts execute the performance analyses. A weights and sizing tool, INTROS (Integrated Rocket Sizing) in concert with the structures tool (LVA, Launch Vehicle Analysis), and the trajectory tool Program to Optimize Simulated Trajectories (POST) to develop the initial concept and vehicle description. The information describing the vehicle is typical in the form of a detailed mass breakdown structure. Analysts using the NASA/Air Force Cost Model (NAFCOM), the reliability/safety model FIRST, and operations models assess the life cycle cost of the concepts. Each of the concepts is analyzed using this process trading technologies or other features of the concept until technical programmatic feasibility is achieved. INTROS, POST, and LVA are tools that are commonly used within the Advanced Concepts Office. Operations, cost, and reliability are provided by other organizations supporting the studies.

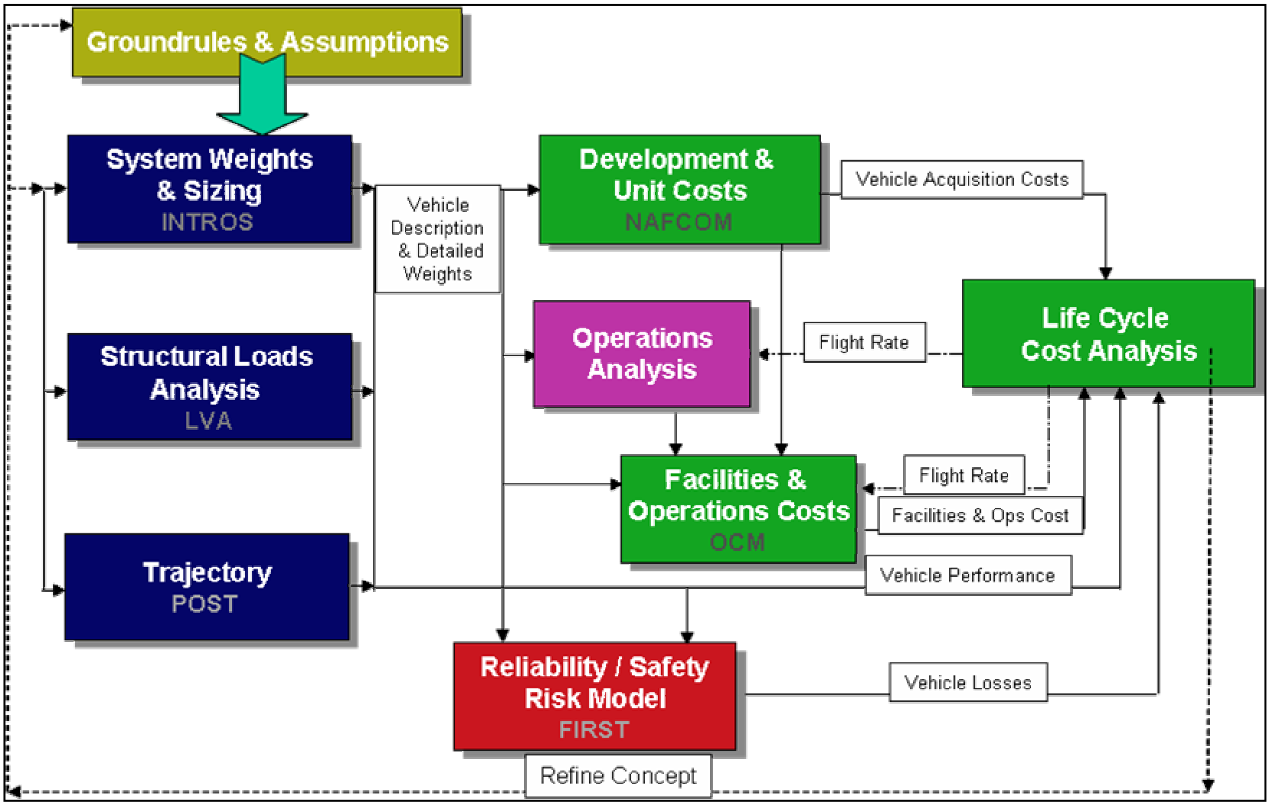

Figure 3. ETO Concept Analysis Process Example

1.2.1 INTROS[1]

INTROS is written in Visual Basic for Applications and uses Excel for input and output. INTROS was developed to expedite conceptual and preliminary design work on launch vehicles. It can help the launch vehicle designer with 1) vehicle architecture, 2) launch vehicle sizing, 3) technology and system trade studies, and 4) parameter sensitivity studies. Stage geometry is established using geometric shapes available in Excel. Using these shapes basic drawings can be made of all of the body structures. Stages are scaled automatically to improve one of four optional resizing parameters: stage specific propellant mass fraction, vehicle propellant mass fraction, vehicle ideal velocity, or total mass of ascent propellant.

INTegrated ROcket Sizing Model (INTROS) is an Excel Workbook, Visual Basic language based analytical tool that is used to perform conceptual and preliminary design sizing and trade and sensitivity studies for launch vehicles and In-Space Chemical Propulsion Stages.

Types of Launch Vehicles:

- **Any number of stages, inline and/or piggy-back**
- **Liquid, solid, hybrid, airbreathing propulsion systems**
- **Mono-propellant, bi-propellant, tri-propellant**
- **Pump-fed or pressure-fed**
- **Expendable or recoverable**

Can automatically resize stages to improve mass fraction

Layout drawing capability

Developed in-house by Emory Lynn

Version 4.1 released in September, 2005

Enables increased modeling fidelity w/faster turnaround

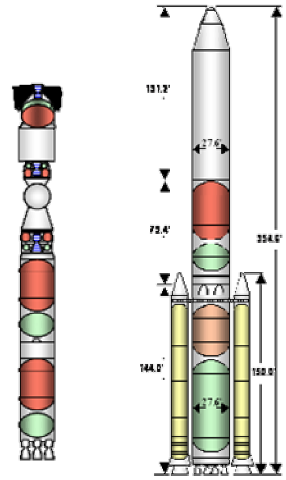

Figure 4. INTROS Overview

1.2.2 LVA

The structural loads and structural sizing for the launch vehicle as well as other similarly configured stages are analyzed using a stand alone application written in Visual Basic called LVA (Launch Vehicle Analysis). The program calculates aerodynamic loads and structural weights based on the material properties, load factors, stress, elastic stability, deflection among other structural analysis parameters. The tool does not use weight estimating or scaling equations, but is a solution to closed form equations used to model structural elements and vehicle components. As a result of LVA many analyses that used to require multiple hours or days can now be completed in just minutes.

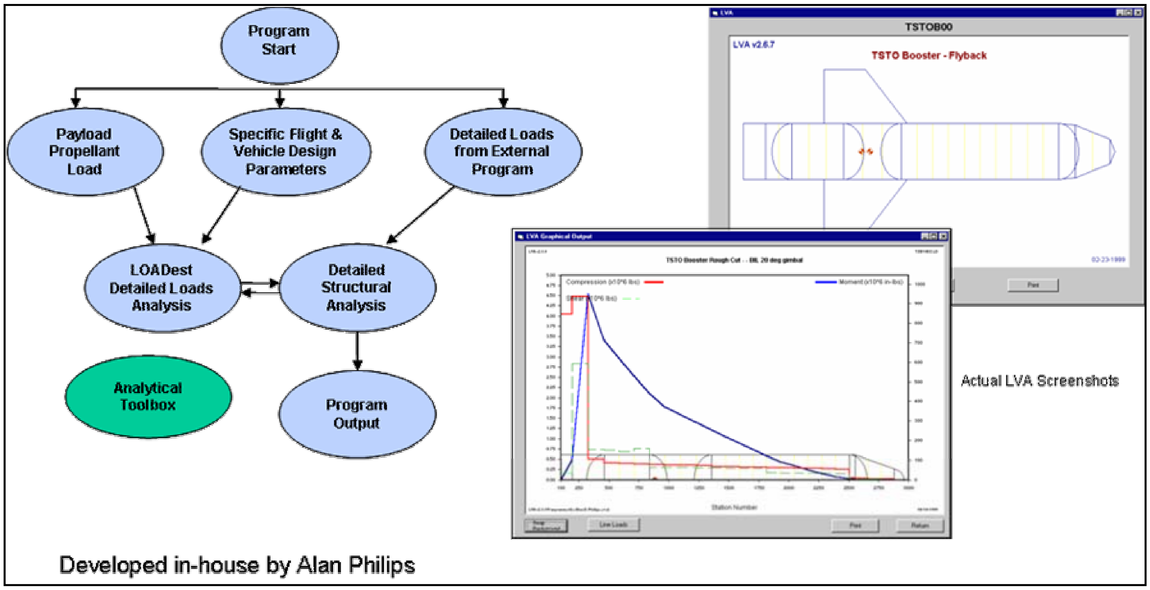

Figure 5. LVA Overview

1.2.3 Trajectory Tools

Depending on the level of fidelity required, a systems analysis of a concept will need trajectory analyses. Figure 6 shows the tools typically used in the trajectory modeling in Advanced Concepts. Of those listed the Program to Optimized Simulated Trajectories[2] (POST) is the most common. It is a general purpose FORTRAN program for simulating and optimizing point mass trajectories for aerospace vehicles. It is used to solve a wide variety of mission analysis problems for atmospheric and orbital vehicles. Most commonly in Advanced Concepts it is use for ascent trajectories. However, it has been used for reentry and descent trajectories. The other tools shown in the figure are used, but not as widely as POST.

POST is used for high thrust applications. Low-thrust propulsion applications, such as interplanetary or lunar trajectories, require a different type of analysis tool. The tools ChebyTOP (Chebychev Trajectory Optimization Program) and VariTOP (Variable Calculus Trajectory Optimization Program) are used to mode the very sensitive trajectories that involve low thrust such as that generated by a solar electric propulsion stage. Figure 6 is a listing of the tools used at MSFC and examples of the output of the tools. Figure 7 is a listing of low-thrust trajectory tools available for use or currently being developed under the Low Thrust Trajectory Tool (LTTT) project being managed and led out of MSFC.

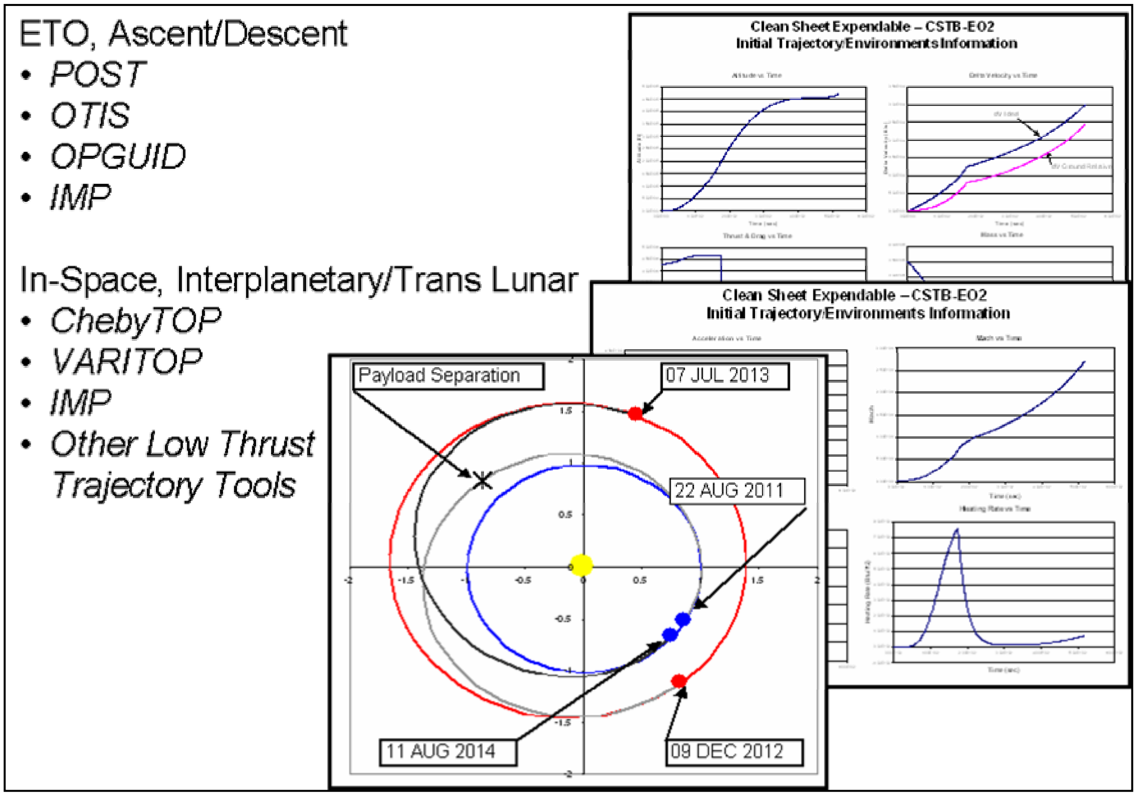

Figure 6. Trajectory Tools

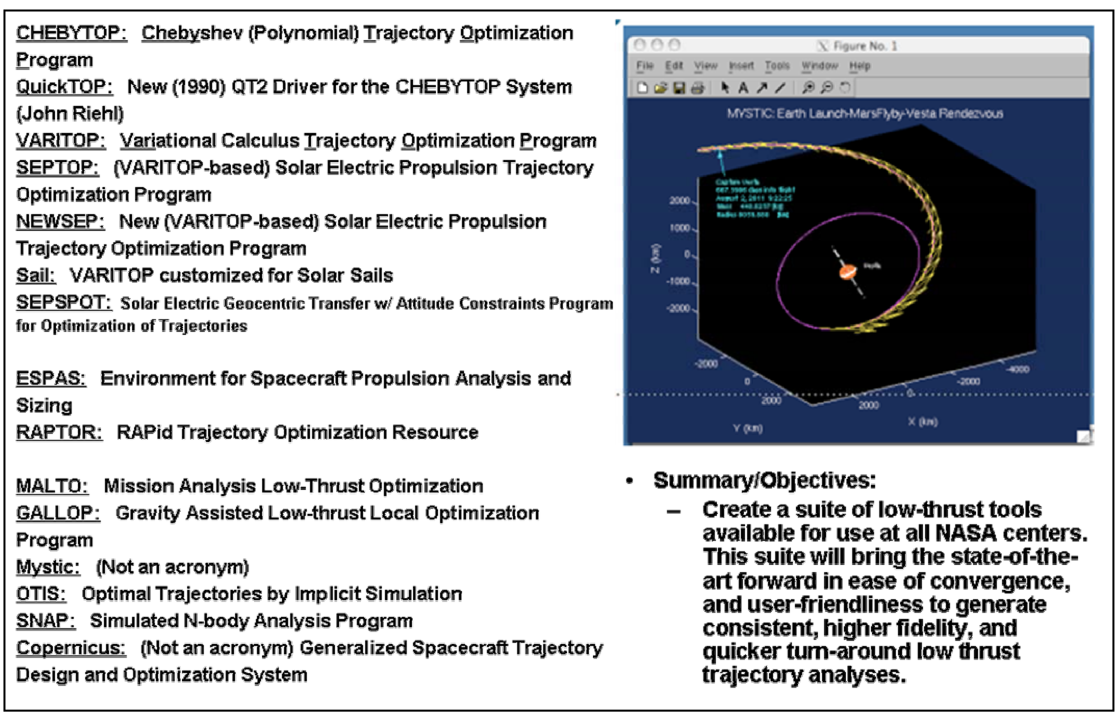

Figure 7. Low Thrust Trajectory Tool Suite

1.2.4 Preliminary Analysis of Space Exploration Concepts (PARSEC)

PARSEC is a toolset and design environment that allows study leads to create and maintain projects and studies in an organized way, enabling team members to easily compare and contrast similar data between studies and individual concepts. PARSEC allows the study lead to organize large projects into smaller individual efforts that are presented more easily later. The principal focus of PARSEC is on collaborative analysis and design. PARSEC allows members of a design team to run analysis tools and to store and share data in a central data repository for incorporation in study deliverables. Analysis in PARSEC is done in user workspaces. Each analyst configures a workspace to run an analysis tool or set of tools, to get input data from the central database and to write result data to that database. There are several pre-defined workspace types, each handled by a Java plug-in (interchangeable software component). Developers can add new workspace types without changing existing source code by writing a set of classes and installing the classes in a configuration file.

Collaboration requires human interaction as well as data-sharing. PARSEC provides instant message and chat room facilities for this purpose. Users may type messages to one another freely, or participate in group discussions in chat rooms. If microphone headsets are available, users can operate voice chat in the same ways. Voice chat is actually more convenient in many ways than telephone interaction. Voice messages may be replayed, for instance, if the receiver misunderstands or is simply away from his/her desk.

Figures 8 shows the PARSEC structure and analysis tools relation to the database. The users interact with the database and the tools through a graphical user interface an example of which is shown in Figure 9.

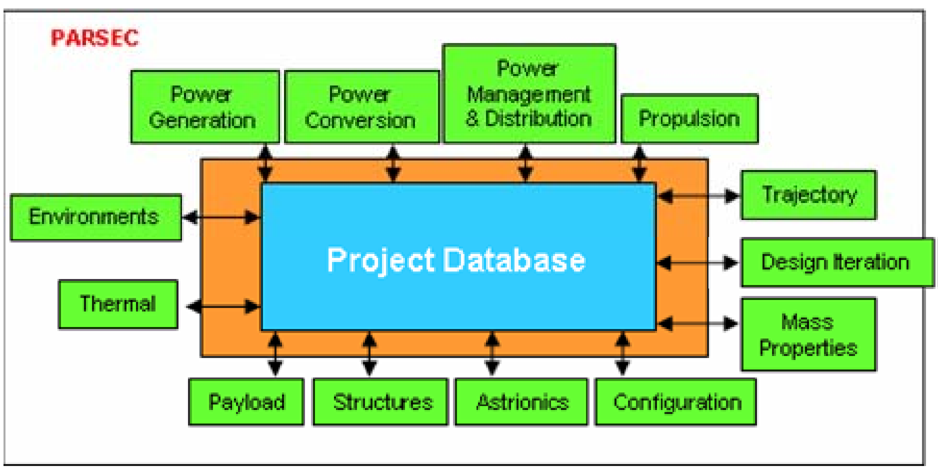

Figure 8. PARSEC Structure

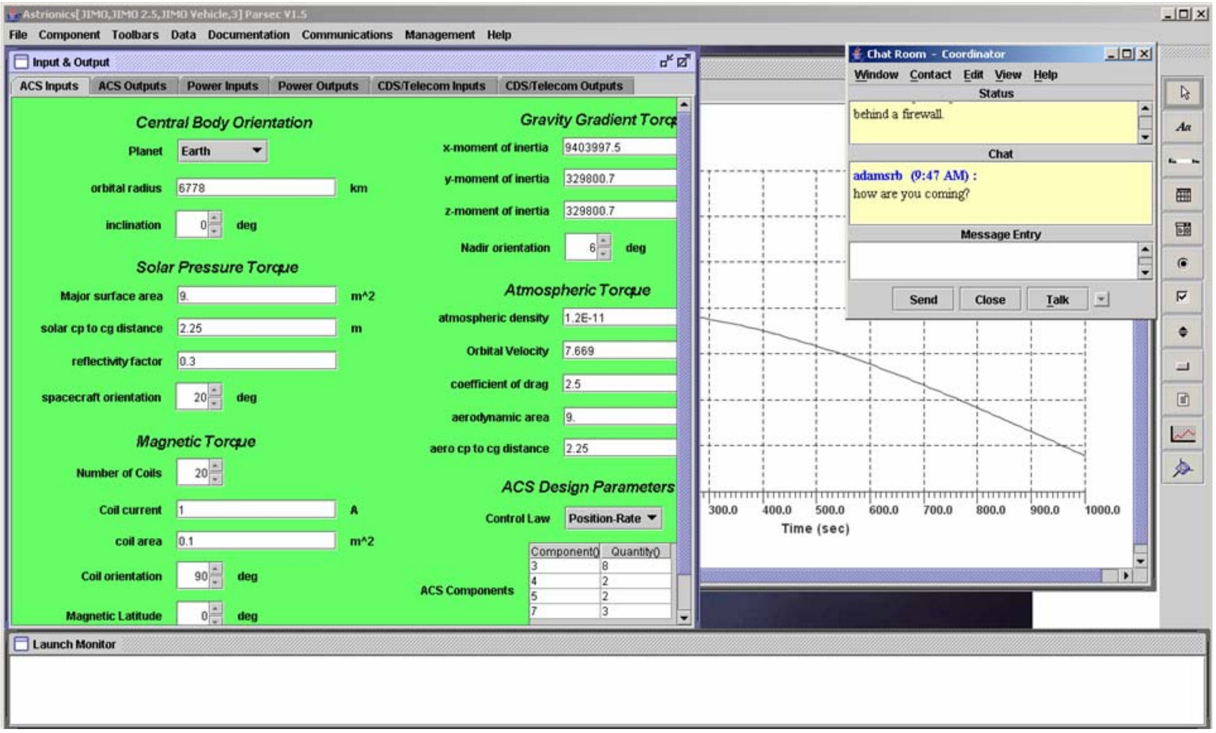

Figure 9. Example of PARSEC GUI

2.0 Advanced Concepts/Vehicle Integrated Performance Analysis (VIPA) Interaction

VIPA is a process of applying existing people, skills and tools to complex problems. The team members of VIPA are generally taken from the Engineering Directorate at MSFC. The VIPA processes are based on traditional Engineering capabilities, and its tools and models have been exercised and validated extensively. The VIPA team performs more detailed integrated modeling analyses which make it a very good fit with the Advanced Concepts Office. Once the high level trades are completed in Advanced Concepts the VIPA can take the information and perform more detail trades.

Figure 10 is an example of concepts that have originated in the Advanced Concepts office and were then transferred to the VIPA team for further analyses. The CAD information for the Prometheus boost stage concept was shared electronically with the more detailed disciplined engineers in VIPA along with all of the design assumptions and trade results. The detailed trades provided insight into modifications in the tank structure and thermal the control design which were not readily apparent in the conceptual design. Similarly for Shuttle-Derived launch vehicles the two organizations have worked to support vehicle sizing and trades.

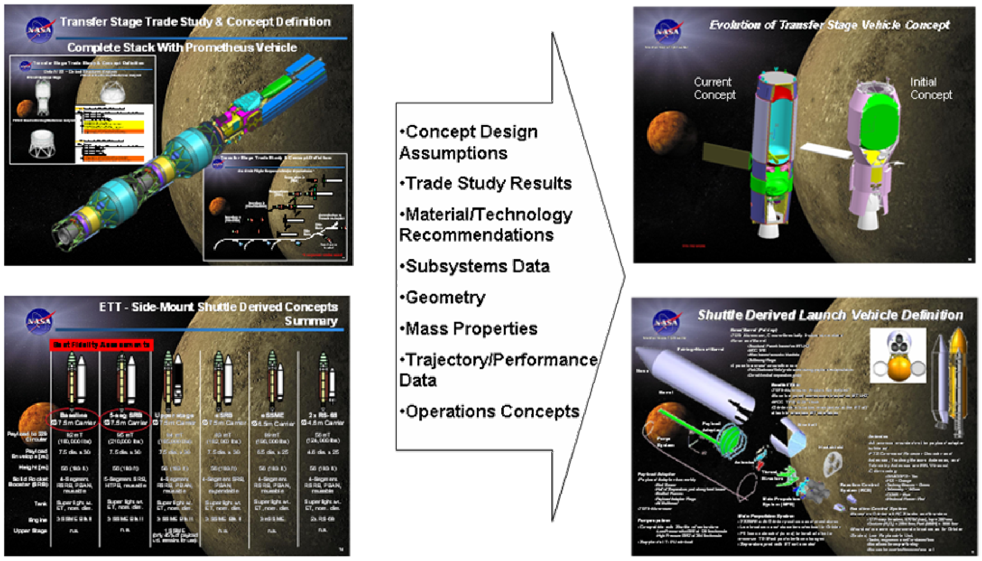

Figure 10. Advanced Concepts to VIPA Transfer

3.0 Summary

Systems analysis and systems engineering at the Marshall Space Flight Center has evolved considerably over the last few years. However, the changes in organization structure have not changed the need to perform conceptual design and detailed trades. The processes shown earlier have enabled MSFC to contribute to the Agency's new exploration programs and point beyond them to more advanced exploration of the universe. The tools currently being used are but a stepping stone to new and better analysis techniques that will be used in the future. No matter what tools and processes used, it is still incumbent on the systems engineers to communicate and foster collaboration that will enable the studies to be completed with acceptable results.

4.0 References

[1]Lynn, Emory E., INTROS User's Manual, pp. 1-1, 1-2.